

Mechanical and electrochemical characteristics evaluation in annealing treatment for ship material

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Abstract: The effect of heat treatment on the electrochemical and mechanical properties of SS400 steel was investigated, and the effects of annealing conditions on notched specimens subjected to the slow strain rate test (SSRT) were studied. The results show that no correlations are observed among the maximum tensile strength, yield strength, and stress corrosion cracking. In contrast, the elongation and time-to-fracture are improved with stress-relieving annealing compared with the as-received condition. The elongation, time-to-fracture, and number of dimples increase with annealing heat treatment.

Key words: heat treatment; SS400 steel; electrochemical and mechanical properties; slow strain rate test; stress corrosion cracking

1 Introduction

On- and offshore structures located in severe marine environments must be protected to reduce corrosion, and the corrosion resistance of a material is one of the most important factors for ensuring the long life of such structures. Most marine structures, such as static platforms, are fixed and submerged under seawater and thus are difficult to repair and maintain. Moreover, the costs of inspections and maintenance are high. Corrosion and stress corrosion cracking (SCC) are factors in most accidents involving marine structures [1–2]. Although in general, corrosion has little influence on the static tensile strength of high-strength steel under high residual stress, embrittlement fractures, fatigue fractures, and SCC can deleteriously affect high-strength steel [3–8]. In contrast, mild steel with little residual stress does not undergo hydrogen embrittlement or SCC. Therefore, the improvements of SS400 steel after annealing heat treatment were investigated using electrochemical and slow strain rate tests.

2 Experimental

For the electrochemical experiments, the SS400 steel was mounted in an epoxy resin so as to leave an exposed area of 100 mm² that was polished with No.600

emery paper. The electrochemical apparatus consisted of a Pt coil as the counter electrode and an Ag/AgCl saturated KCl as reference electrode. A scan rate of 2 mV/s was applied in natural seawater. Anodic polarization experiments were executed from an open circuit potential (OCP) to 3.0 V after immersion for 3 600 s. Cathodic polarization experiments were undertaken from OCP to –2.0 V. The annealing condition was heated to 550 °C, and kept for 1.0 h, followed by furnace cooling. The SSRT was carried out in seawater using an Instron instrument (Model #8516). The size of test specimens was 280 mm×15 mm×10 mm (length×width×thickness). Notches were made on both sides of parallel parts of the specimens to cause a fracture. The SSRT was carried out at a strain rate of 0.005 mm/min in air and seawater.

3 Results and discussion

Fig.1 plots the potential against immersion time for as-received and annealed SS400 steel. In the early stage of immersion in seawater, the potential of as-received sample quickly shifted in the negative direction, and stabilized after approximately 1 500 s. In contrast, the potential of the annealed specimen stabilized at –0.53 V after 1 200 s. The potential remained steady until 4 000 s. Subsequently, the value shifted in a negative direction. Independent of heat treatment, the potentials after

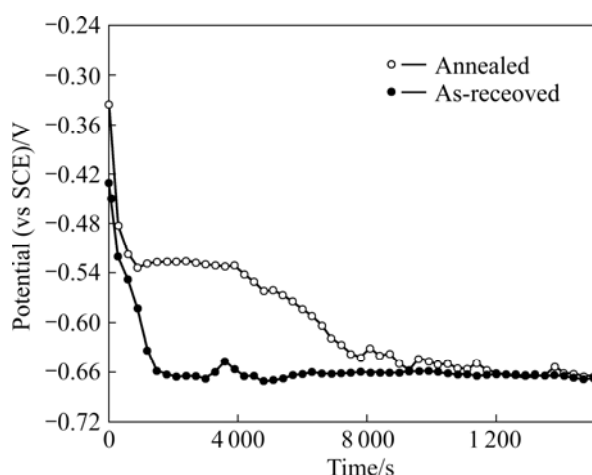


Fig.1 Open circuit potential with immersion time for as-received and annealed SS400 steel

immersion for 12 000 s were similar. Overall, the potential of the annealed specimen had a noble value compared with the as-received specimen.

In general, an annealing treatment causes high-strength steel that is subject to high residual stress to become more ductile, while relieving the residual stress. Consequently, the softening of steel is improved through hydrogen embrittlement and SCC. It is believed that SS400 steel subjected to a small amount of residual stress gains greater corrosion resistance from an annealing treatment as a result of relieving the residual stress. Therefore, the potential of annealed specimens shifts in the noble direction.

Fig.2 shows anodic polarization curves of specimens, after immersion for 3 600 s. The potentials of the annealed and as-received specimens were -559 and -634 mV, respectively, demonstrating that annealing improved the anticorrosion property. The current density increased steadily with increasing potential above the

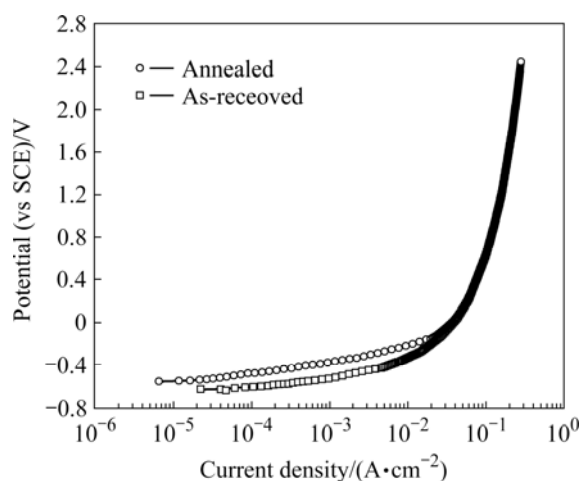


Fig.2 Anodic polarization curves of SS400 steel

OCP. The current density from the OCP to 0 V in the annealed specimen was low. Conversely, the current densities at a more noble value than 0 V had similar values. Therefore, it can be concluded that under these conditions, annealing had no effect on SCC. It is believed that SCC occurs at an applied potential in the anodic direction at an OCP.

Fig.3 displays the cathodic polarization curves. The cathodic polarization trend for SS400 showed the effects of concentration polarization due to oxygen reduction and activation polarization due to hydrogen generation. The anticorrosion property was improved due to annealing at an observed current density corresponding to the concentration polarization range of dissolved oxygen reduction. The current density in the annealed specimen was lower compared with the as-received specimen. The turning point between the concentration polarization and activation polarization occurred at -1.05 V. In addition, the current density with anodic polarization was greater than that with dissolved oxygen reduction during cathodic polarization, which implies that cathodic protection is more economical than anodic protection[9–10].

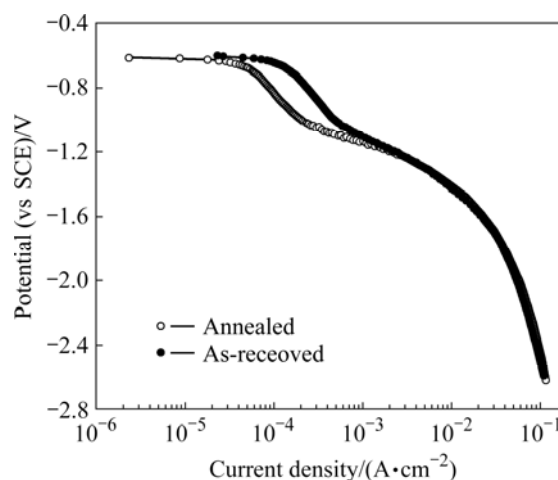


Fig.3 Cathodic polarization curves of SS400 steel

Fig.4 shows the cathodic and anodic polarization curves for as-received and annealed specimens in seawater. The anodic polarization trend showed an active dissolution reaction, while the cathodic polarization trend showed concentration polarization. The two reactions in the annealed and as-received specimens behaved similarly. The corrosion current densities in the as-received and annealed specimens were 1.3×10^{-4} and 3×10^{-5} A/cm², respectively. In addition, annealing improved the corrosion potential[11–12].

Fig.5 illustrates the stress-elongation curves after the SSRT. Although the yield strength, maximum tensile strength, and elongation did not markedly differ, the toughness in air was greater than that in seawater. The

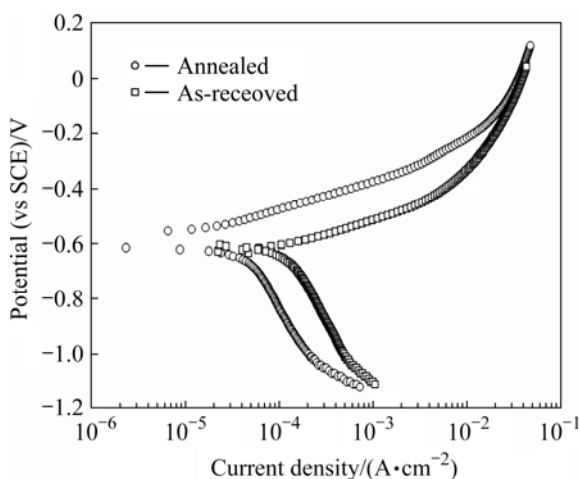


Fig.4 Cathodic and anodic polarization curves of SS400 steel

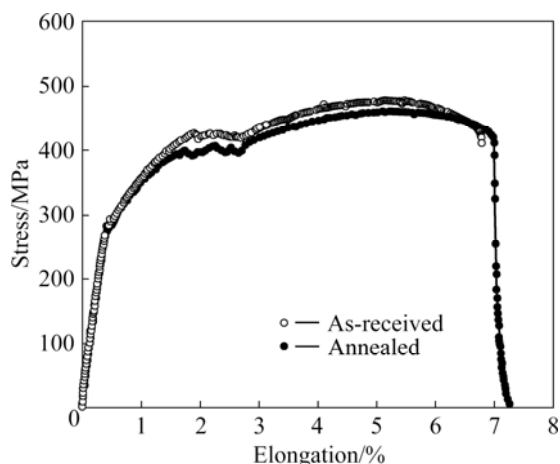


Fig.5 Stress—elongation curves of SS400 steel in seawater

mechanical characteristics of the annealed specimens were better than those of the as-received specimens.

Fig.6 compares the maximum tensile strength and yield strength of as-received and annealed specimens in sea water. Overall, the strength of the annealed

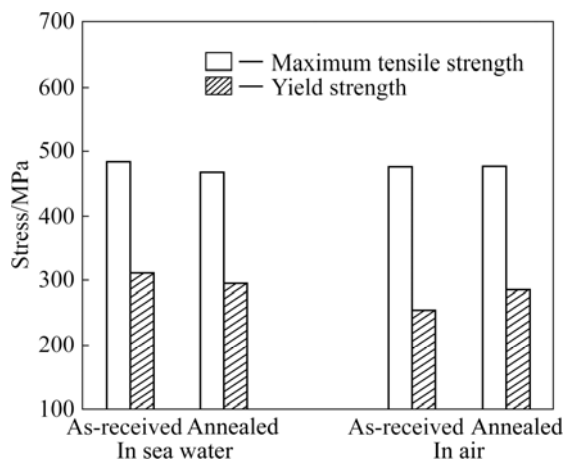


Fig.6 Maximum tensile strength and yield strength of SS40 steel in sea water and air

specimens was lower than that of the as-received specimens. Therefore, annealing decreased the strength of the material as a result of softening it by relieving the stress. While it was thought that the strength generally decreases due to the effect of SCC because of the electrochemical reaction in seawater, no relationship between strength and SCC can be observed.

Fig.7 illustrates the elongation and time-to-fracture of as-received and annealed specimens. The elongation and time-to-fracture in seawater were lower than those in air because only physical force has an effect in air, while physical force and SCC based on the electrochemical reaction occur in seawater. Overall, the elongation and time-to-fracture graphs were similar because the increased ductility resulting from annealing improved the elongation, which increased the time-to-fracture. In the tensile test, no correlation was observed between stress corrosion cracking and the maximum tensile strength or yield strength. Overall, a mutual relationship between SCC and elongation or time-to-fracture can be observed.

Fig.8 and Fig.9 show SEM images of the fractured surface after the SSRT in seawater and air. The fractography observations of the as-received specimen

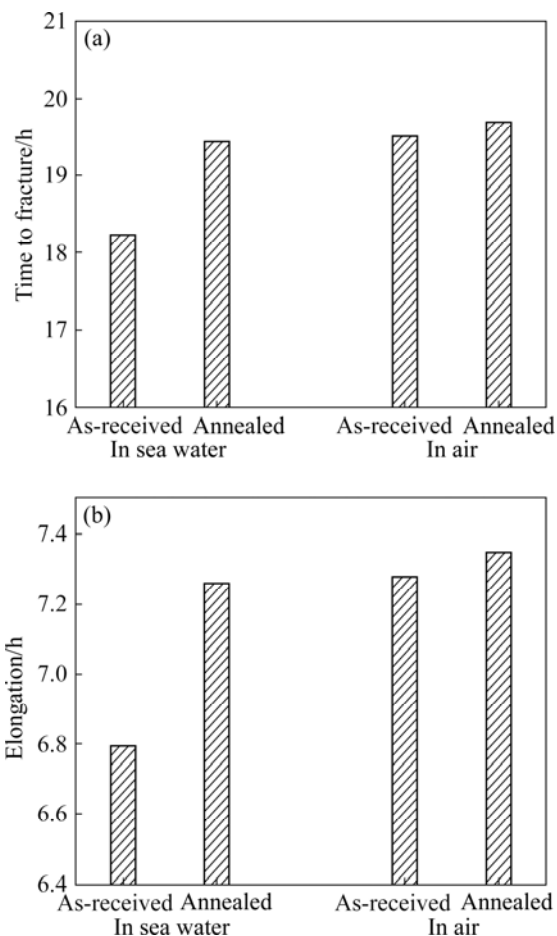


Fig.7 Comparison of elongation and time-to-fracture for as-received and annealed SS400 steel specimens

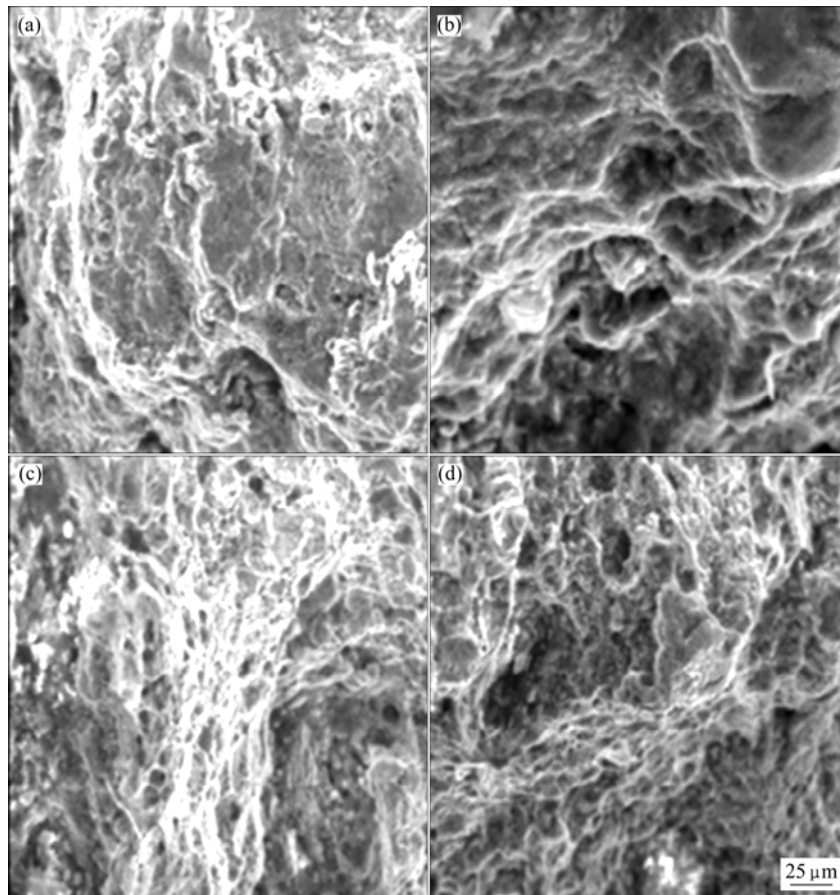


Fig.8 SEM images of fractured surface of SS400 steel after SSRT in sea water: (a) (b) As-received; (c) (d) Annealed

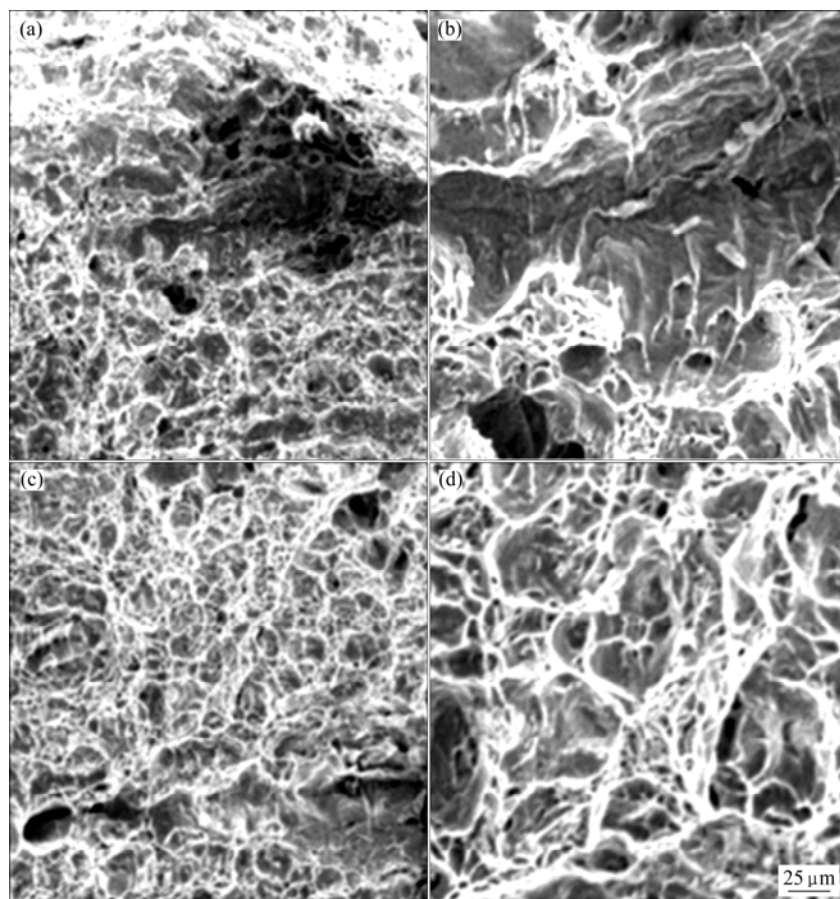


Fig.9 SEM images of fractured surface of SS400 steel after SSRT in air conditions: (a) (b) As-received; (c) (d) Annealed

showed a mixture of dimpling(ductile fracture) and quasi-cleavage (QC). However, the QC fracture pattern was predominant. The QC fractured surface is thought to result from precipitated carbide particles and large impurities and that the dimples on the fractured surface form mainly at the interface between carbide, precipitated material, and metal particles. However, a mixture of dimples and QC fractured surface was also observed in annealed specimens[13].

4 Conclusions

It is believed that mild steel (SS400 steel) subjected to a small amount of residual stress gains greater corrosion resistance from an annealing treatment.

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